Employing recent satellite datasets for improved estimations of the Cloud Radiative Effect and its representation in Climate Models

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with help from Peter Norris, Tianle Yuan, and Dongmin Lee

The problem

• Accurate estimate of the radiative effects of clouds by GCMs

• For simplicity, pick up only one quantity to define the radiative effect of clouds. Let's call it, the "Cloud Radiative Effect" and define it as

$$CRE = C\left[F_{clr} - F_{ovc}(p_c, \tau_c)\right]$$

• You may recognize this as what most people still call "Cloud Radiative Forcing"

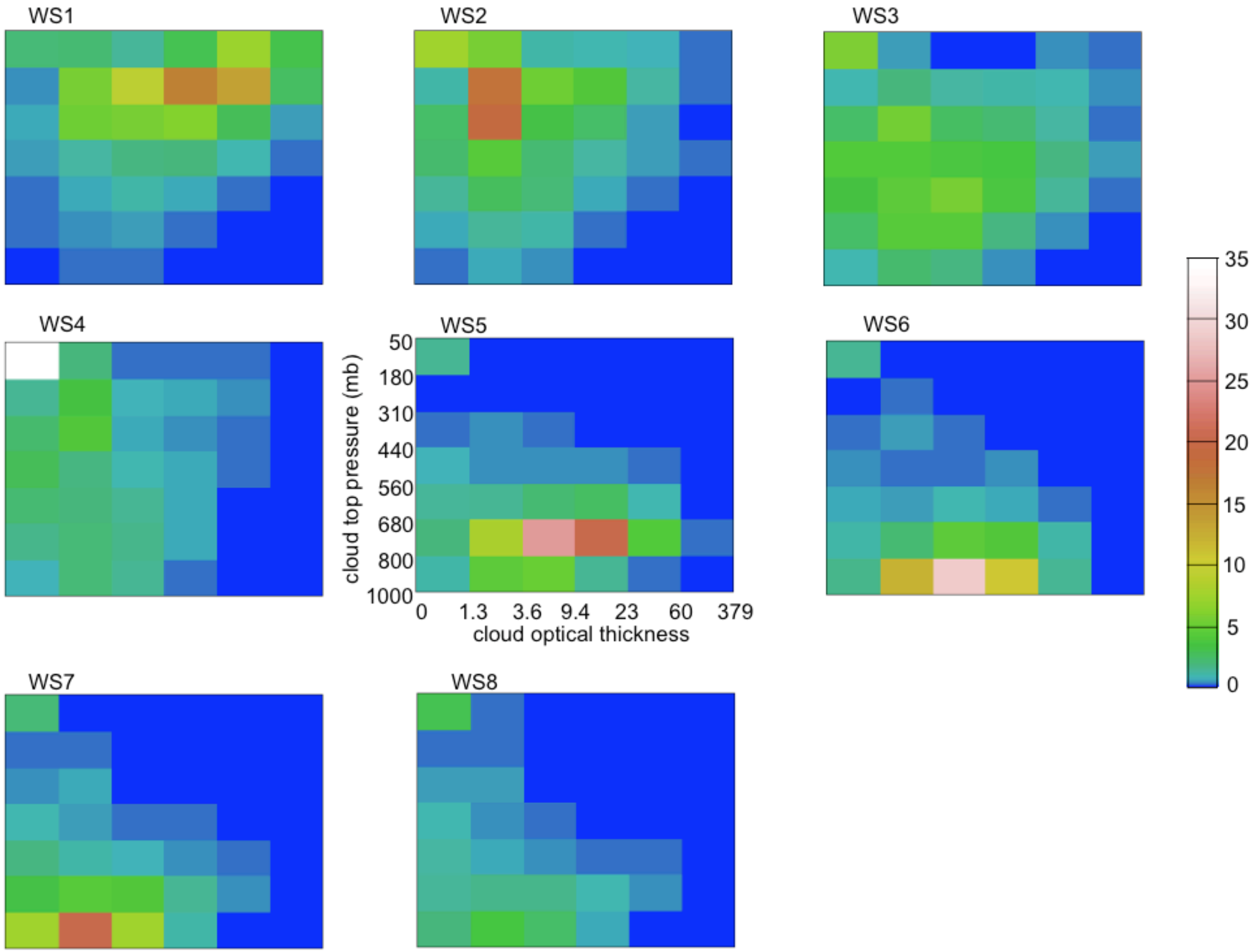
• May refer to TOA, SFC or ATM; ATM may refer to the column or individual layers

•What do we mean by "accurate"? Global mean? Zonal mean? Regional? Annual mean? Seasonal mean? Monthly mean? Diurnal cycle?

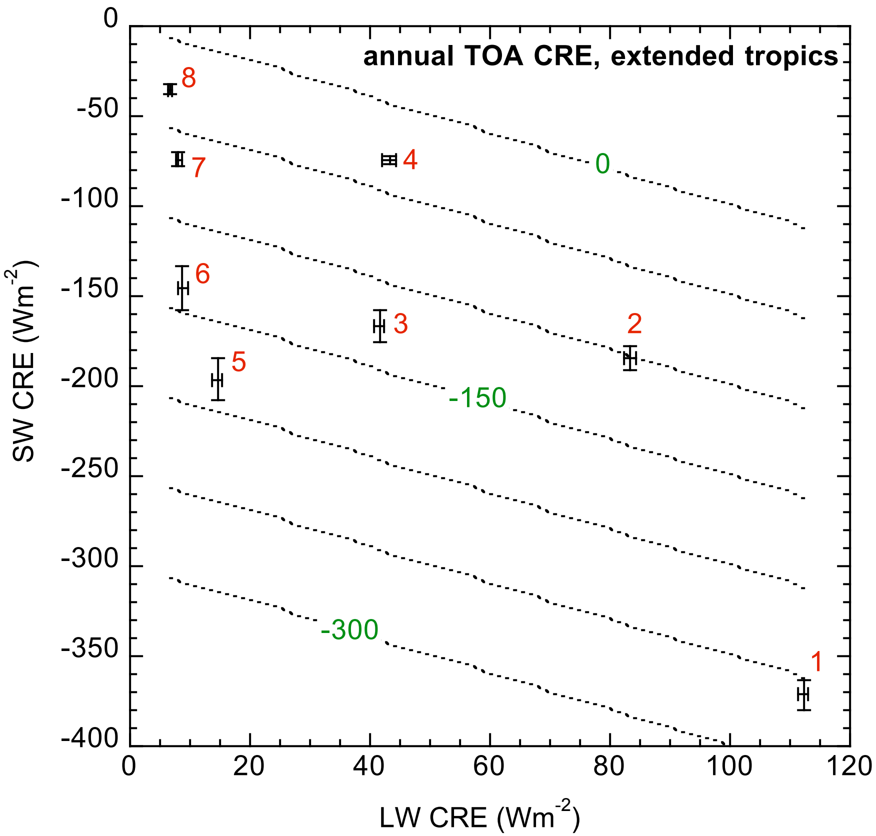
•Can we get all the above "correct" even if the different cloud regimes and their associated CREs are wrong (cancelling errors)

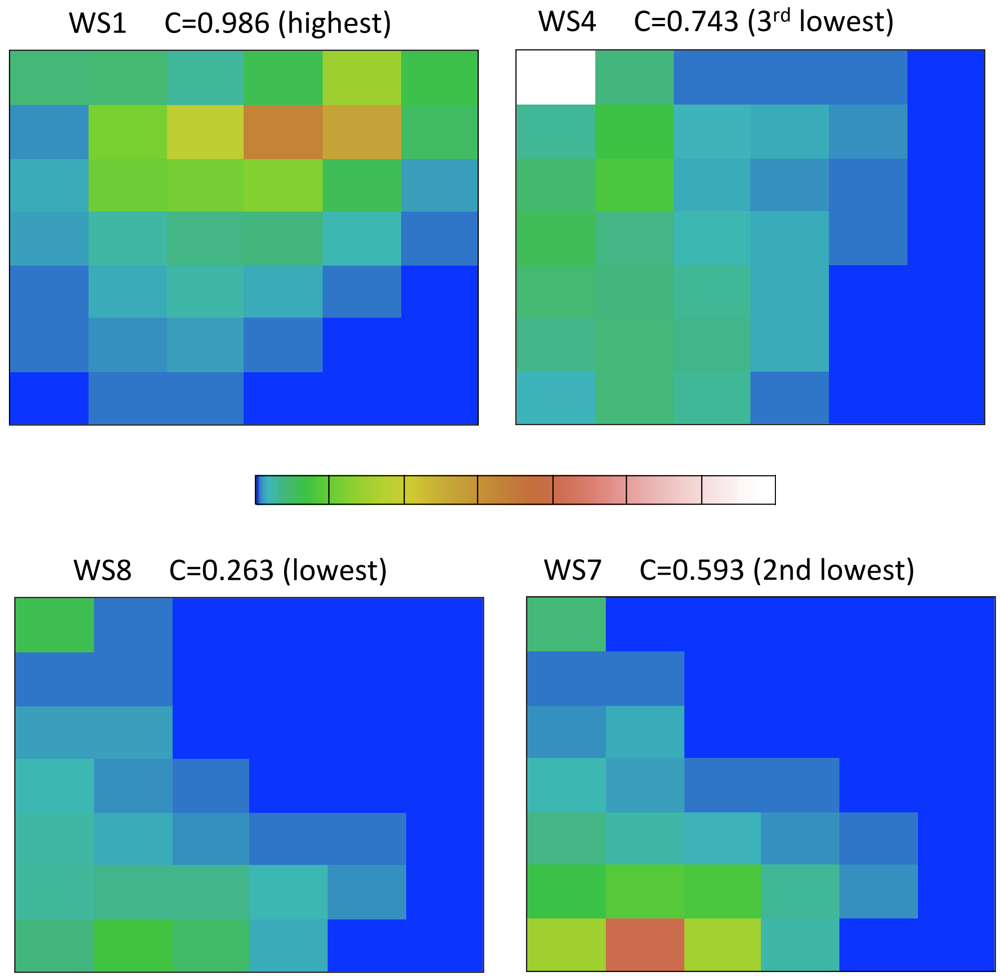
•To what level of detail do we know CRE from observations. e.g., do we know the breakdown by cloud regime (cf. to Huang talk yesterday)?

ISCCP cloud regimes (weather states), tropics



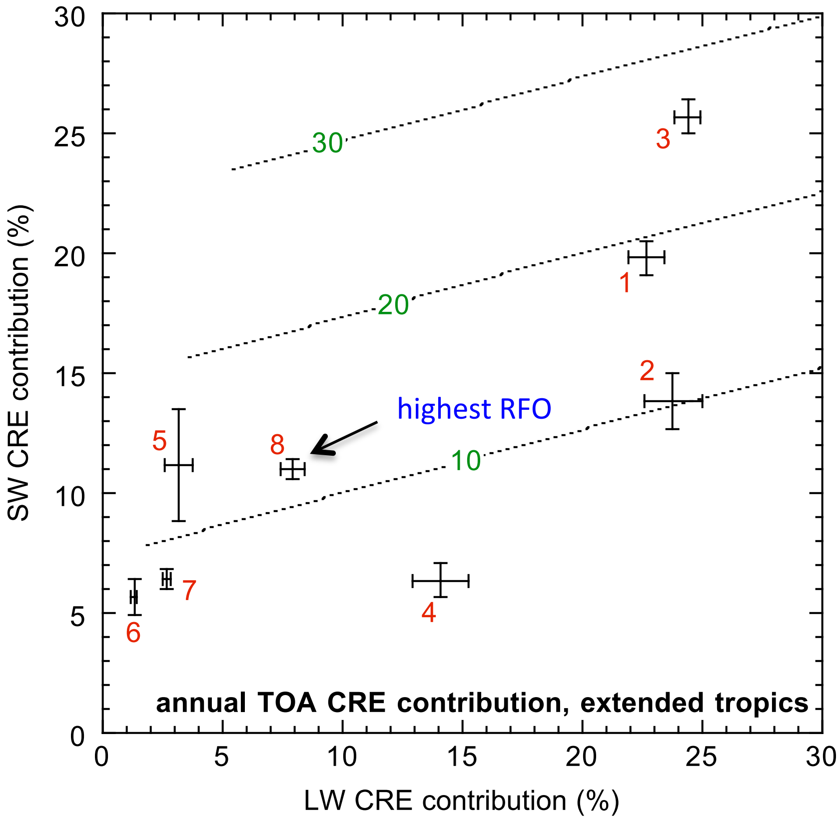
TOA CRE (when present), extended tropics

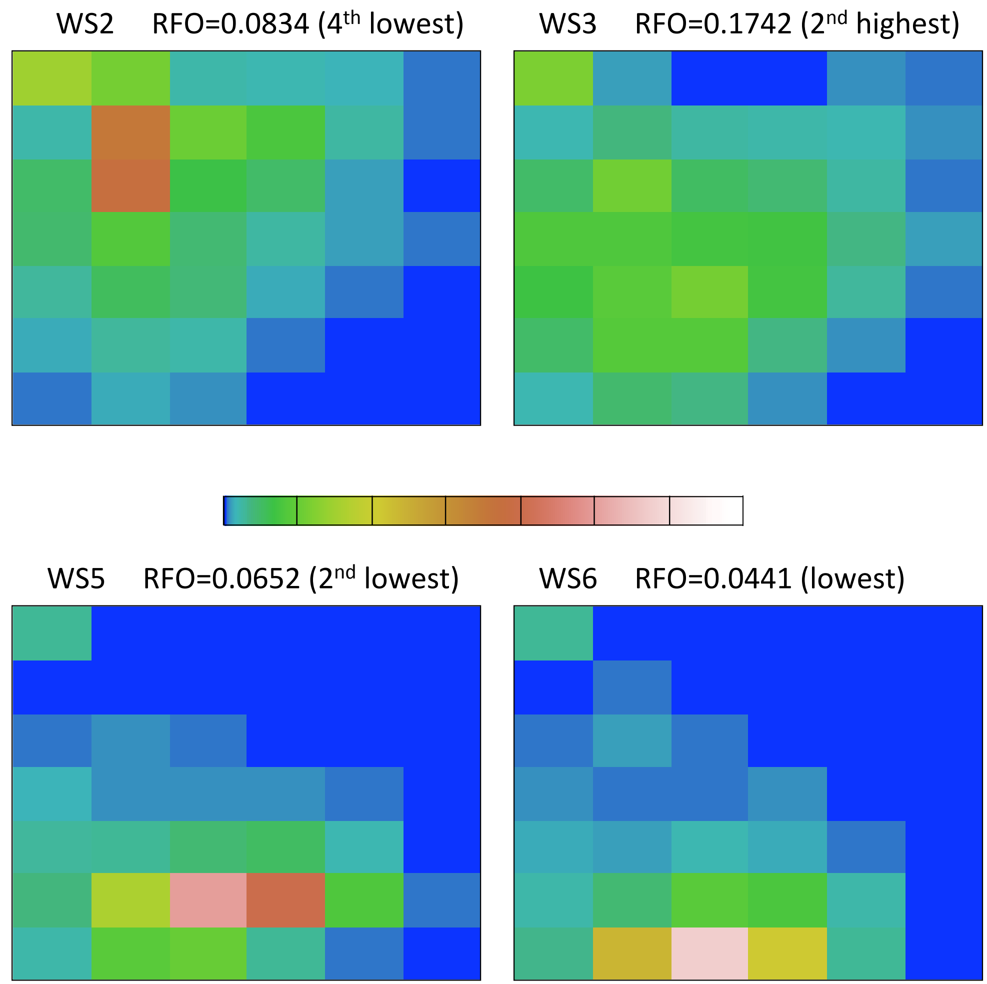




From Oreopoulos and Rossow (2011)

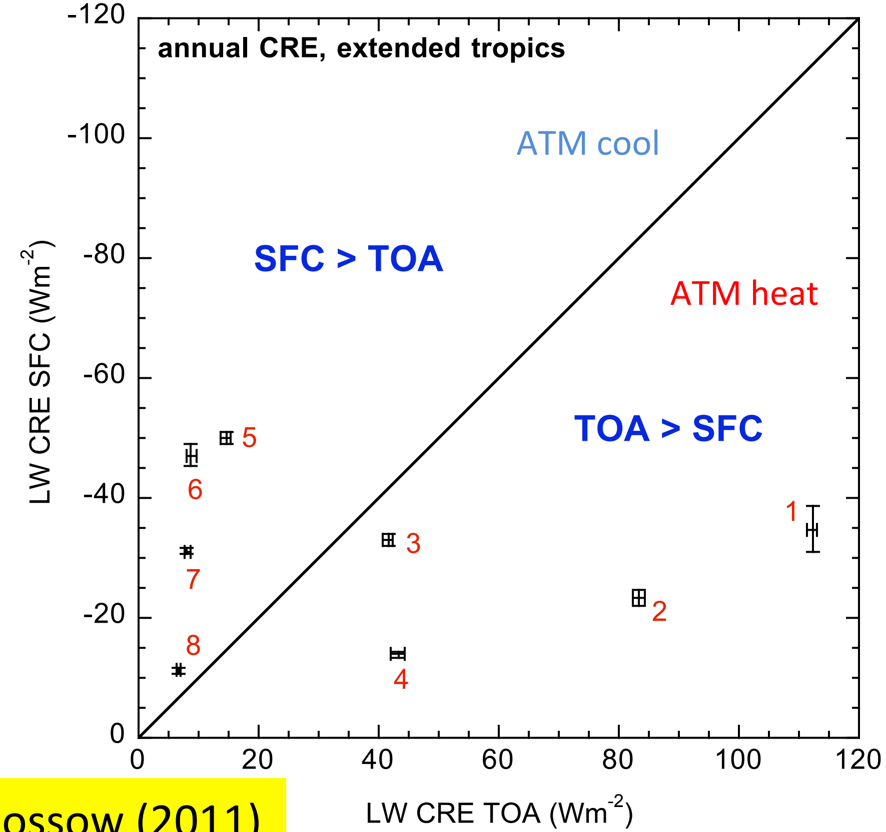
TOA CRE % contribution, extended tropics





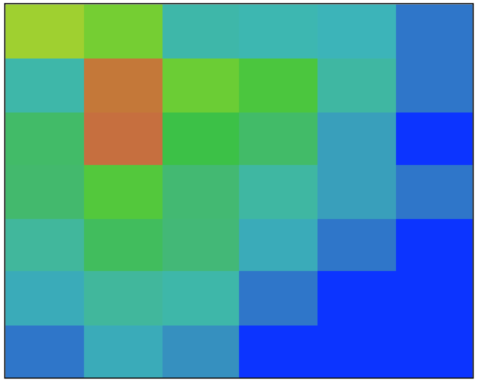
From Oreopoulos and Rossow (2011)

SFC vs TOA LW CRE, extended tropics

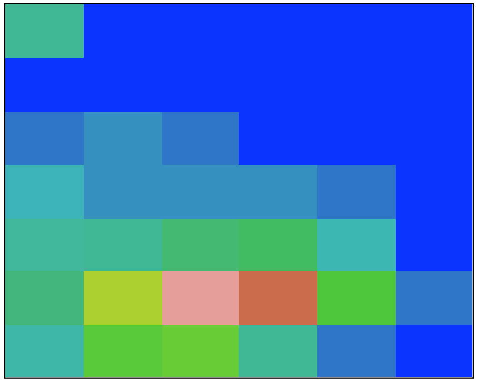


From Oreopoulos and Rossow (2011)

WS2 (RFO=0.0834, CF=0.944)



WS5 (RFO=0.0652, CF=0.845)



What do we need to know in a GCM for accurate CRE from 1-D RT?

•If clouds were single layer, homogeneous, and occupied an exact model vertical layer things would have been rather simple, one basically needs cloud area, vertical location and extinction

$$CRE = C\left[F_{clr} - F_{ovc}(p_c, \tau_c)\right]$$

• But clouds occupy many layers; still, to get TOA and SFC CRE, perhaps the total (vertically-projected) C_{tot}, the total extinction, and the top and base of the highest and lowest cloud would be enough.

•For the vertical profile of ATM CRE more detail is needed

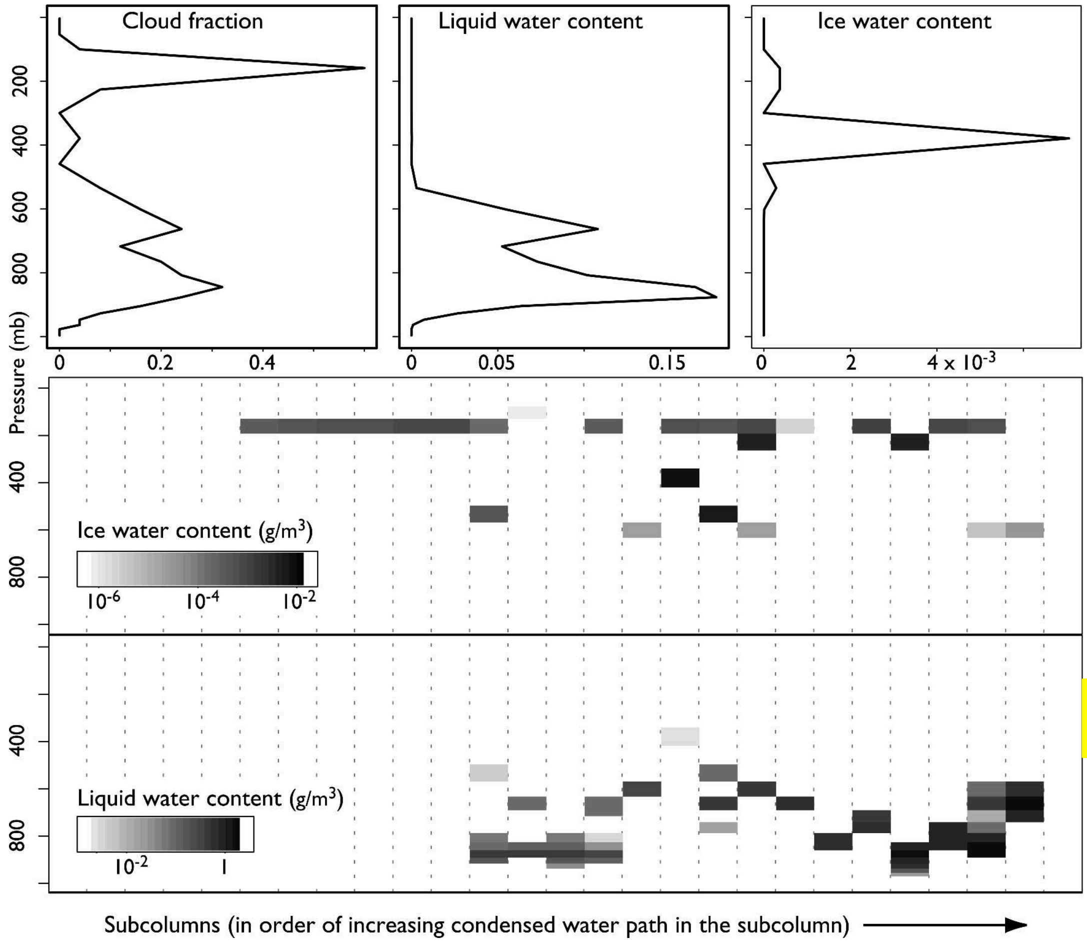
•Actually, even for the TOA and SFC CRE more detail is needed. A profile of C does not give a unique C_{tot} (different cloud overlap)

• Clouds are horizontally heterogeneous in terms of water content (extinction). How do the PDFs overlap?

•Remember that RT (1-D!) calculations in a GCM are performed layer-by-layer

How much do the details matter?

Subcolumn generator and McICA



From Pincus et al. 2006

ICA

$$\overline{F} = \frac{1}{N}\sum_{n=1}^{N} F_n \approx \frac{1}{N}\sum_{n=1}^{N}\sum_{k=1}^{K} f_{n,k} \approx \sum_{k=1}^{K} f_{n_k,k}$$

McICA

(uppercase F is broadband, lowercase f is pseudo-monochromatic)

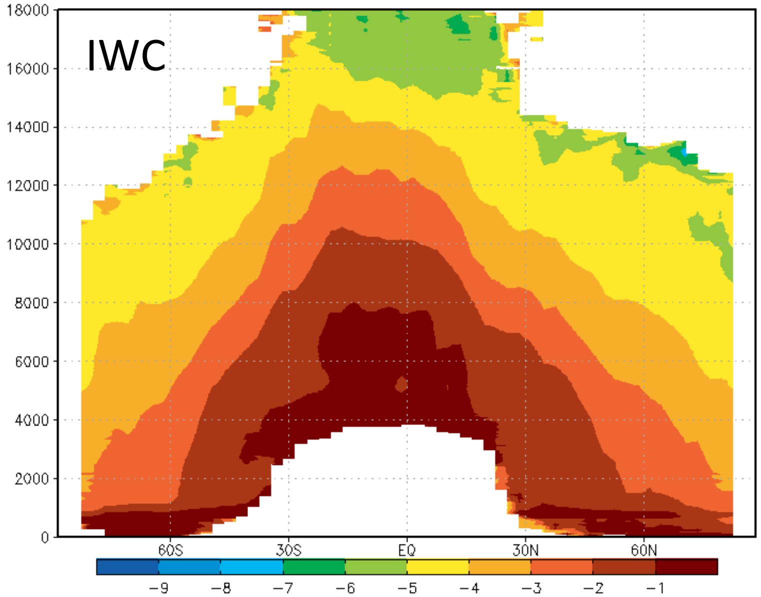
What do we need to know in a GCM for 1-D cloudy RT (continued)

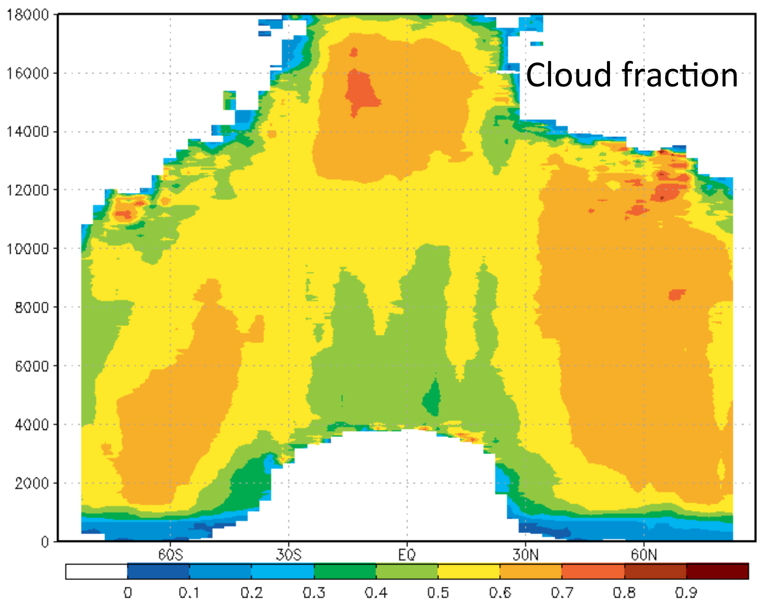
- Cloud fraction profile
- Cloud water profile
- Cloud effective particle size profile
- Cloud variability profile
- How cloud fraction overlaps
- How condensate distributions overlap

- Can GCMs produce the above realistically?
- Are there observations to validate GCMs?
- No profiles with passive
- Profiles possible with active, but there are issues

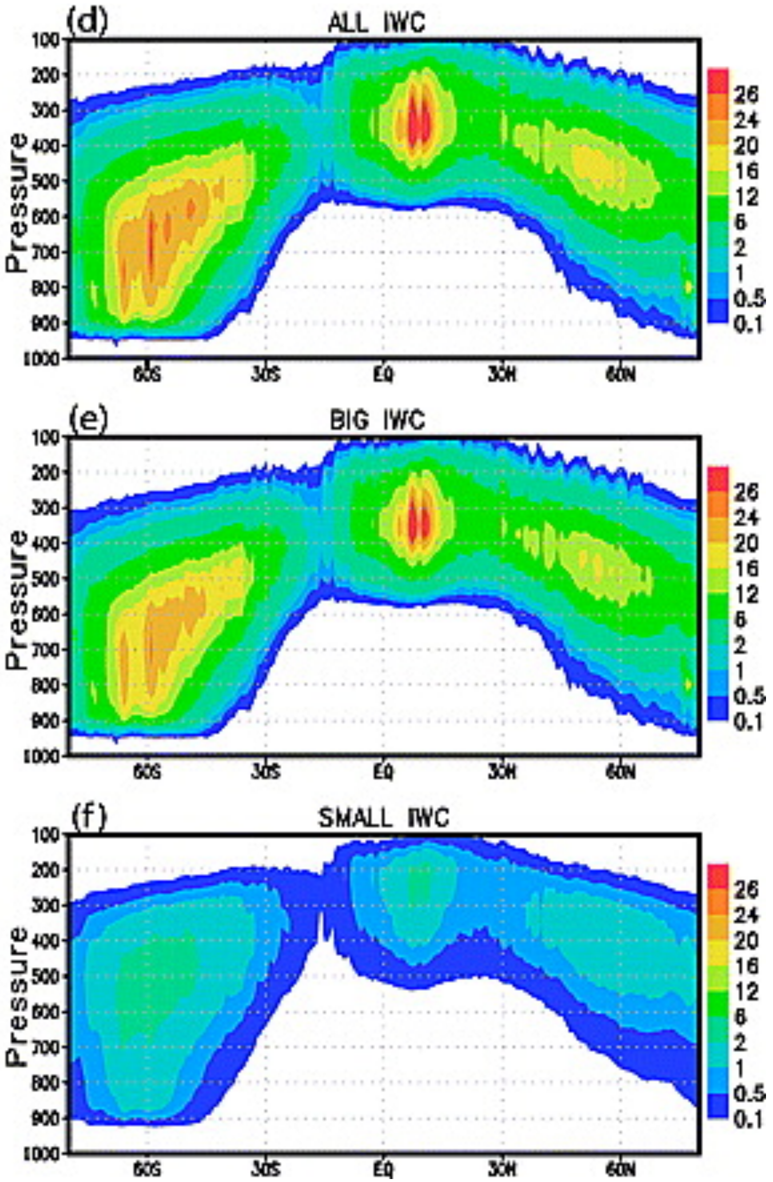
Profiles of cloud fraction and condensate

Ice clouds from CloudSat/CALIPSO (hydrometeors vs. condensate)





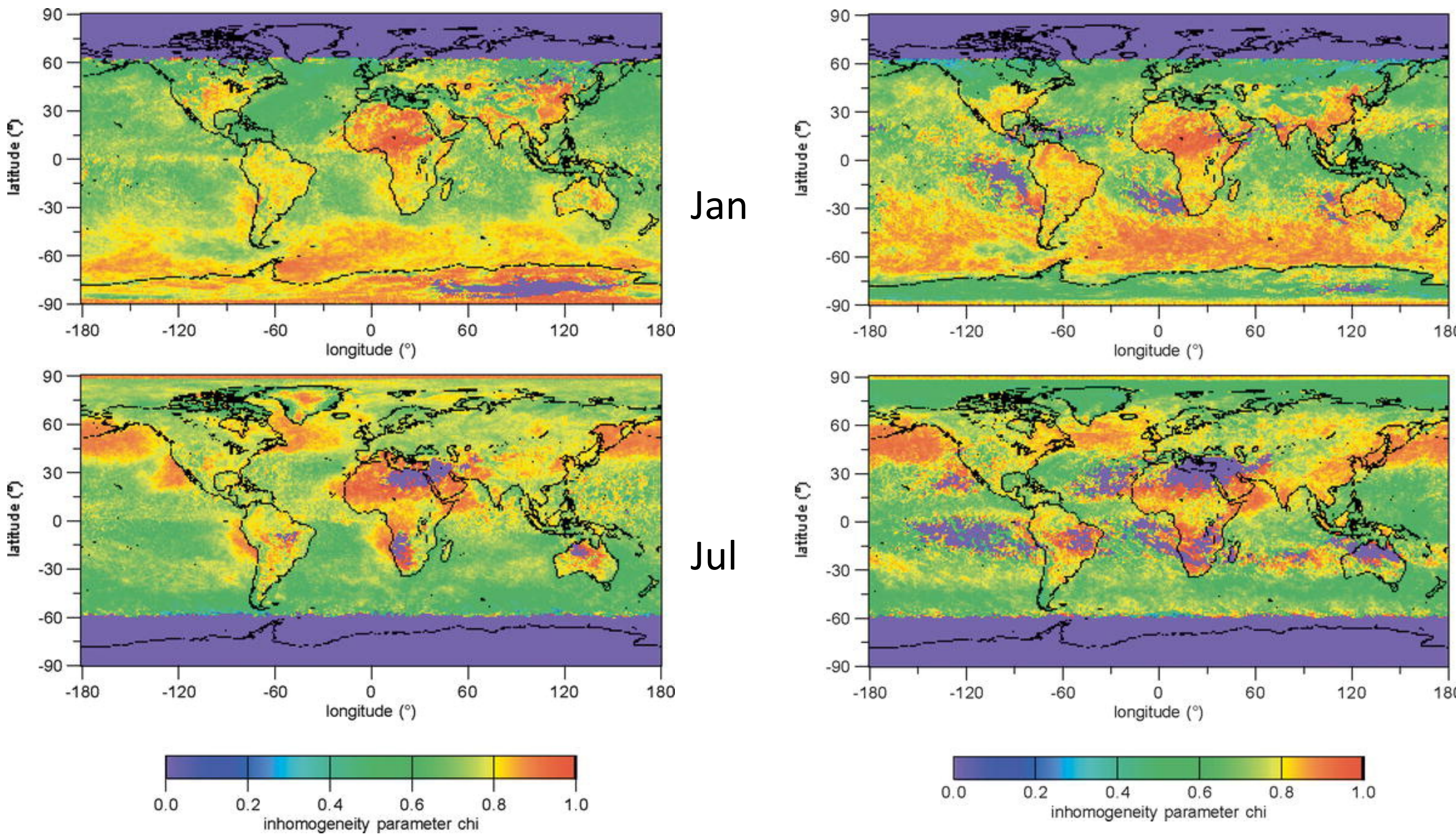
Jan 2009, DARDAR product



From Waliser et al. (2011)

Profiles of condensate variability

Variability of column optical depth from passive (MODIS) 1 degree



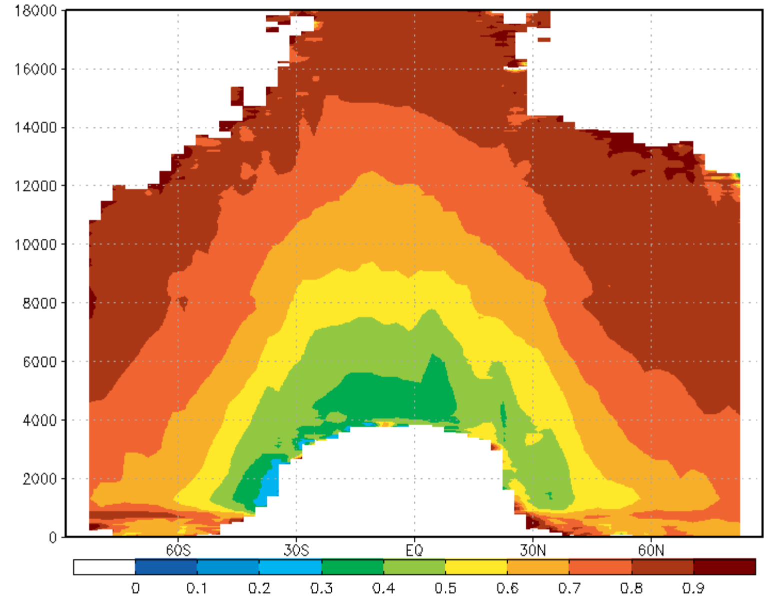
liquid

ice

$$\chi = \frac{e^{\overline{\ln \tau}}}{\bar{\tau}}$$

Variability (spatial) of IWC from CloudSat/CALIPSO ~170 km

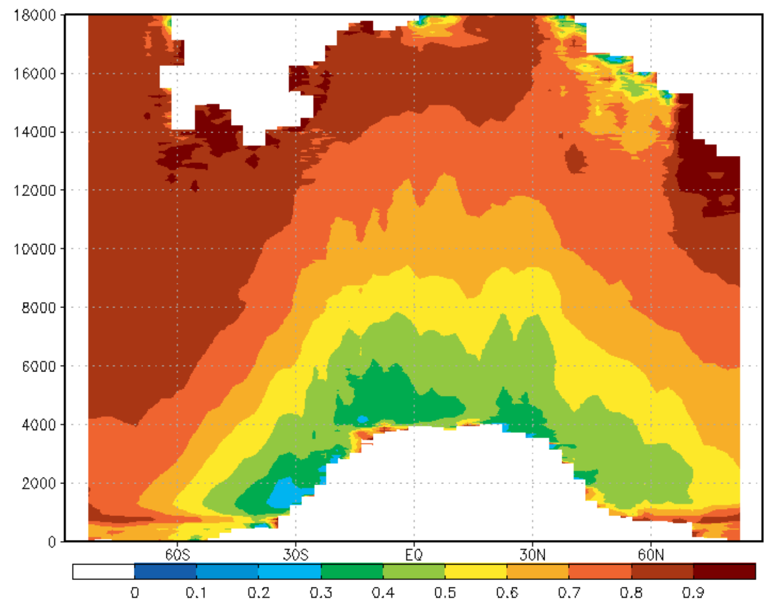
January 2009



$$\chi = \frac{e^{\overline{\ln IWC}}}{\overline{IWC}}$$

DARDAR product

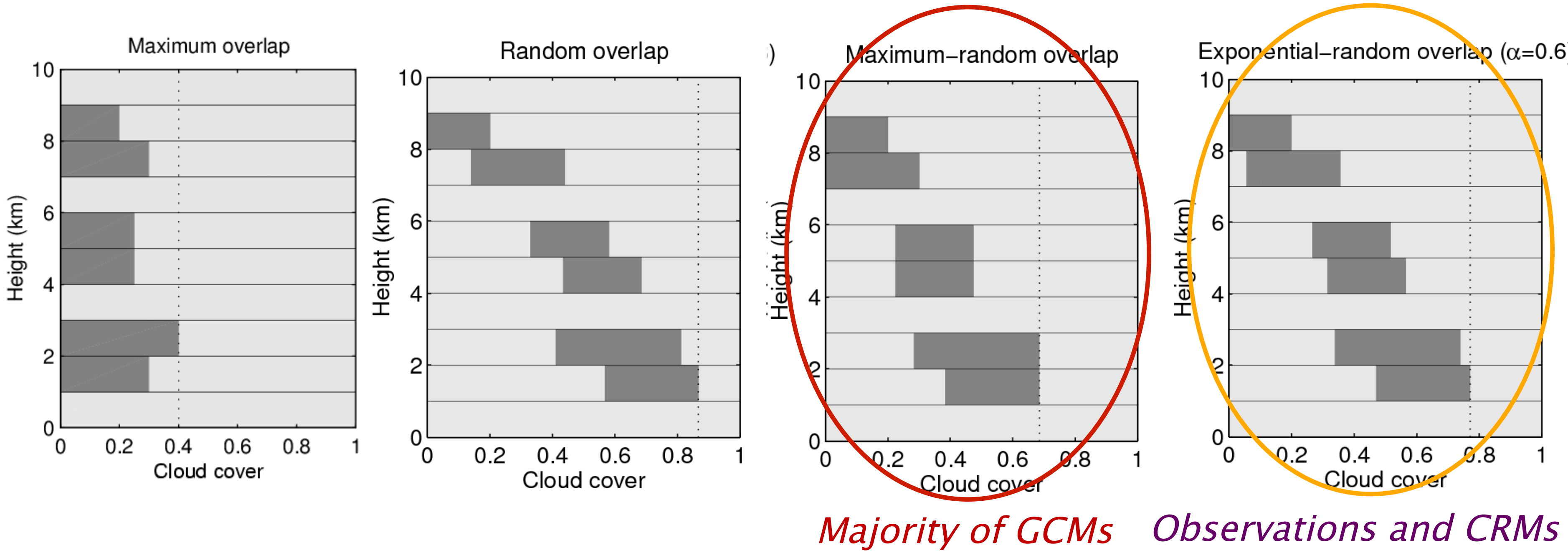
July 2009



See also CloudSat LWC distributions by Lee, Kahn and Texeira (2010)

Cloud fraction overlap

Cloud fraction overlap

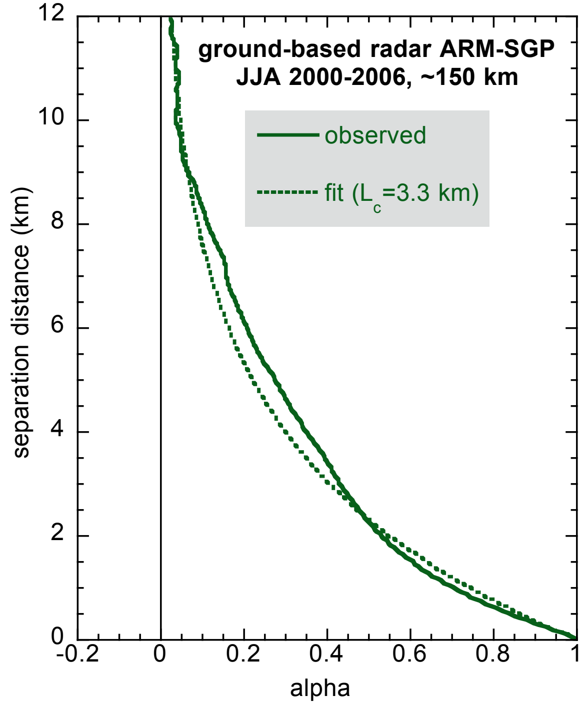


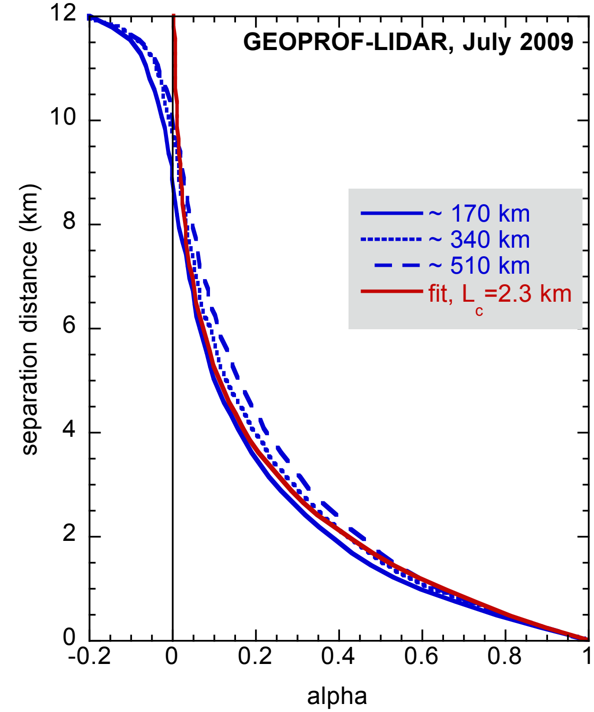
- The same profile of layer cloud fraction can give different total (column) cloud fraction
- Radiative impact (instantaneous) estimates have been as high as 250 Wm^{-2} (high sun)

$$C_{\text{tot}}(\Delta z) = aC_{\max}(\Delta z) + (1-a)C_{ran}(\Delta z)$$

$$a = a(\Delta z, x, y, z, t)$$

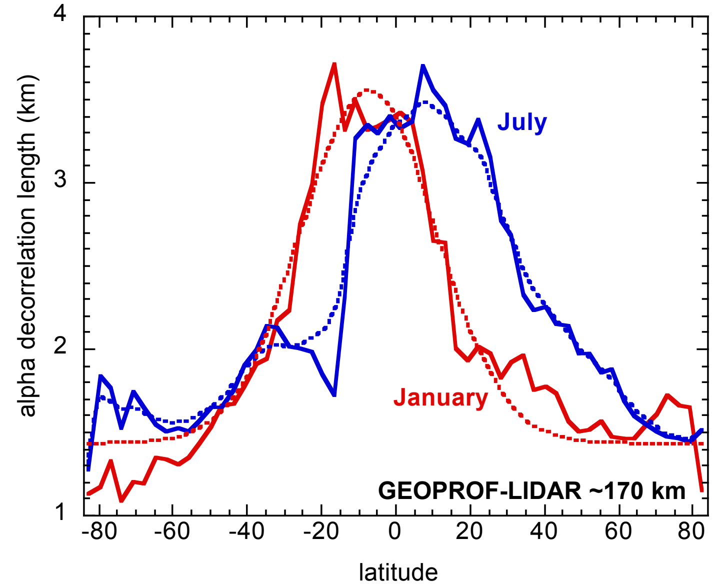
Observed cloud fraction overlap from radar





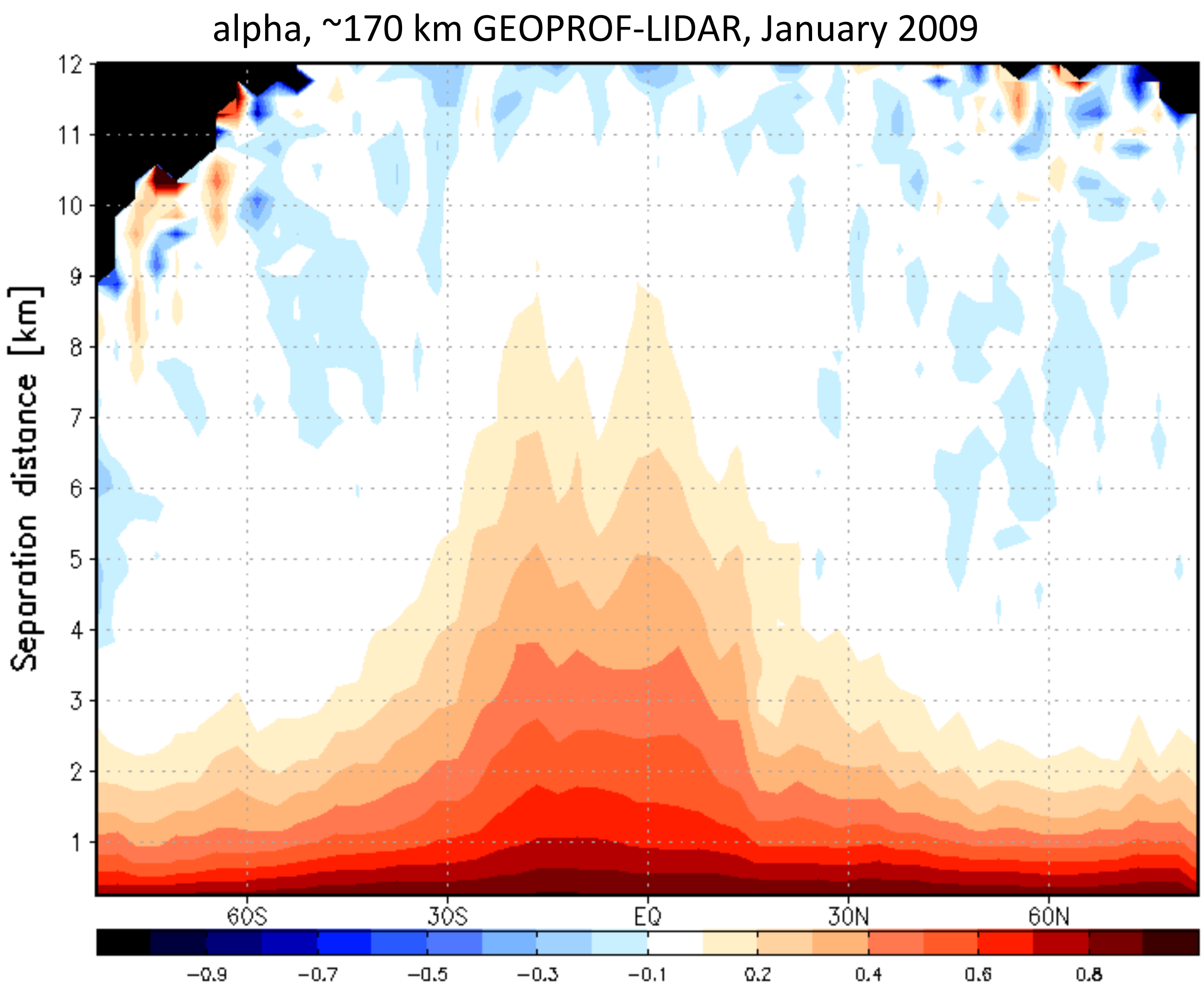
$$a(\Delta z,\bar{x},\bar{y},\bar{z},t) = \exp(-\frac{\Delta z}{L_c})$$

$$L_c = L_c(\bar{x},\bar{y},\bar{z},t)$$



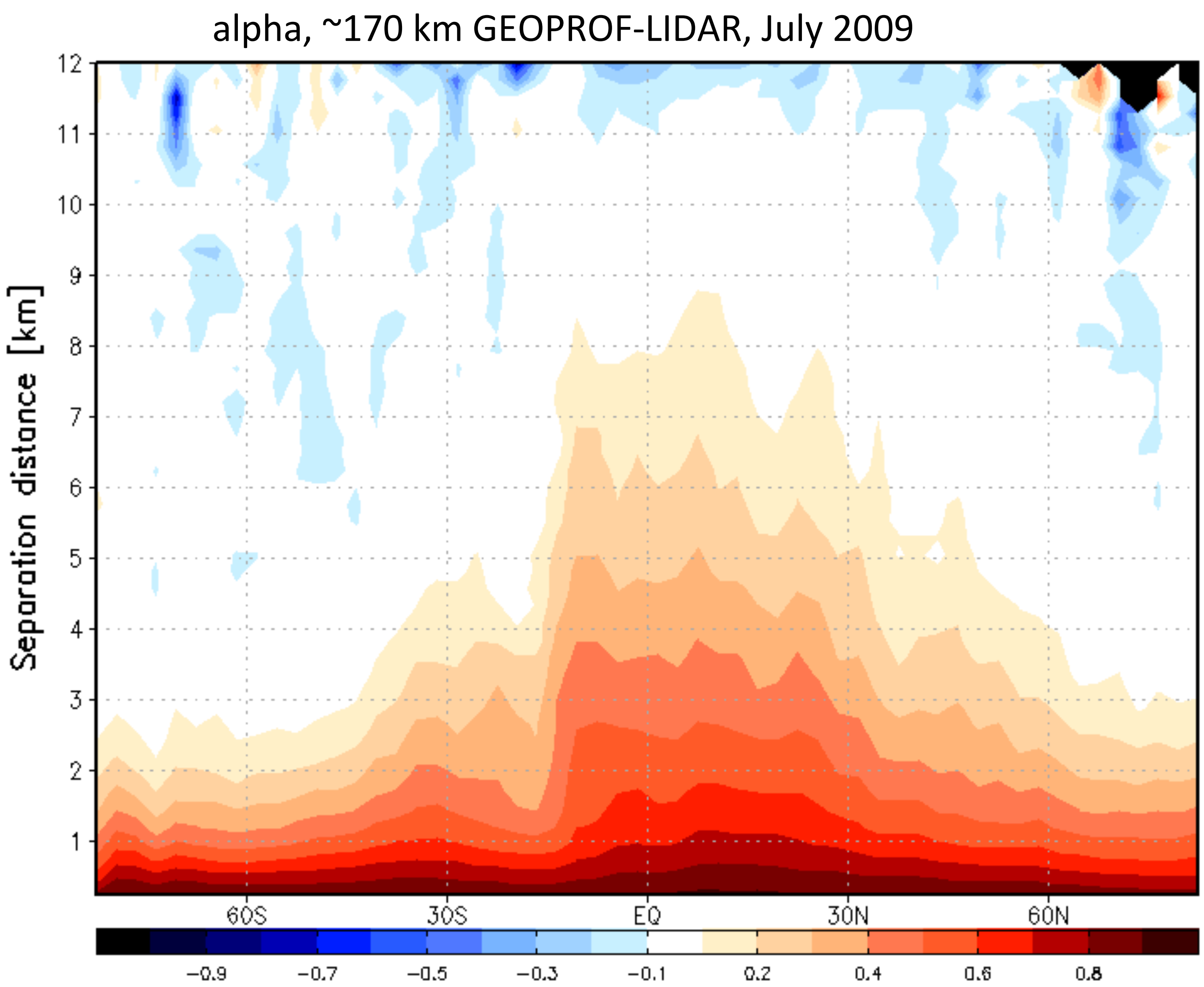
$$L_c = L_c(\bar{x},y,\bar{z},t)$$

Zonal alpha from CloudSat/CALIPSO

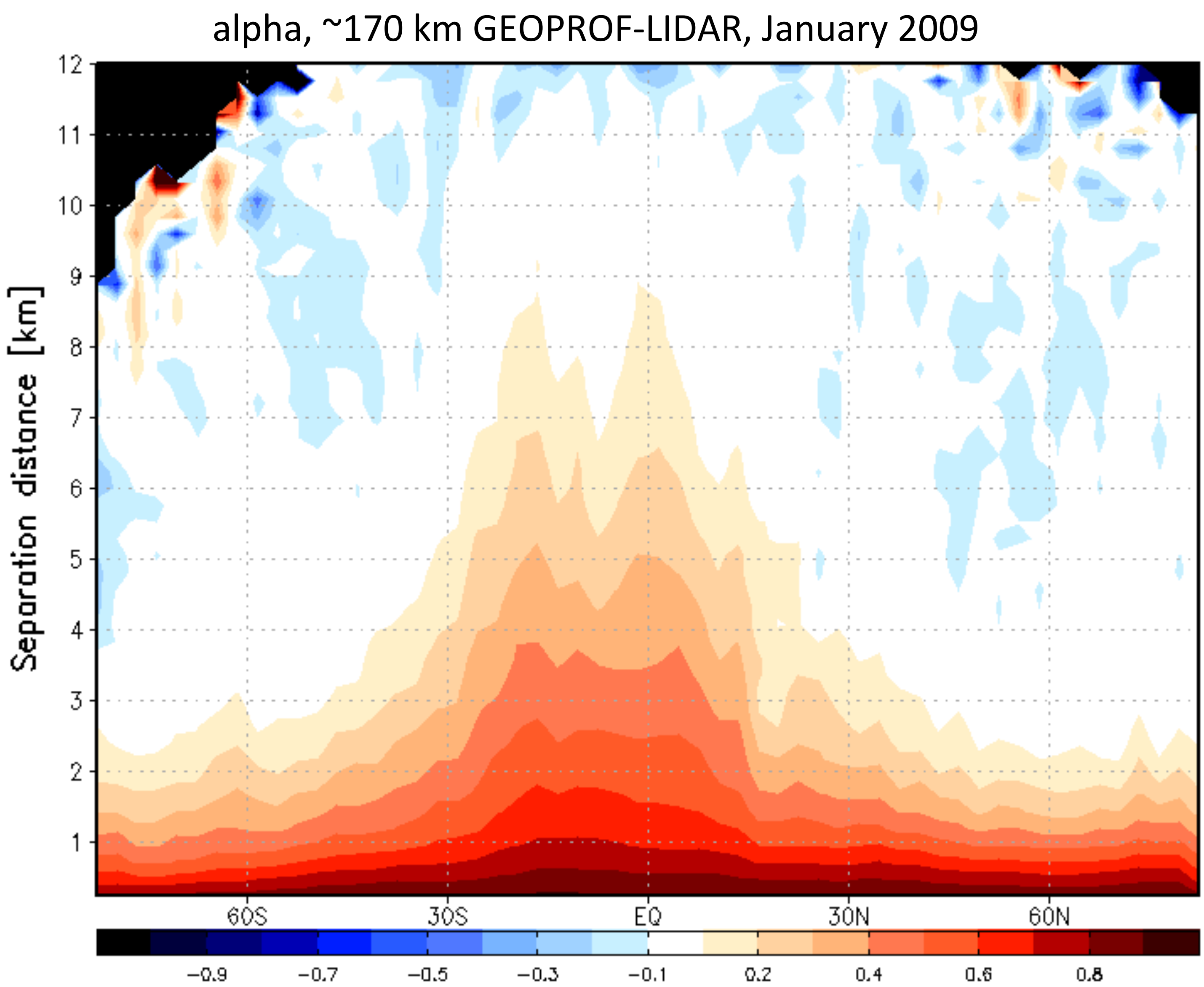


$$a(\Delta z, \bar{x}, y, \bar{z}, t)$$

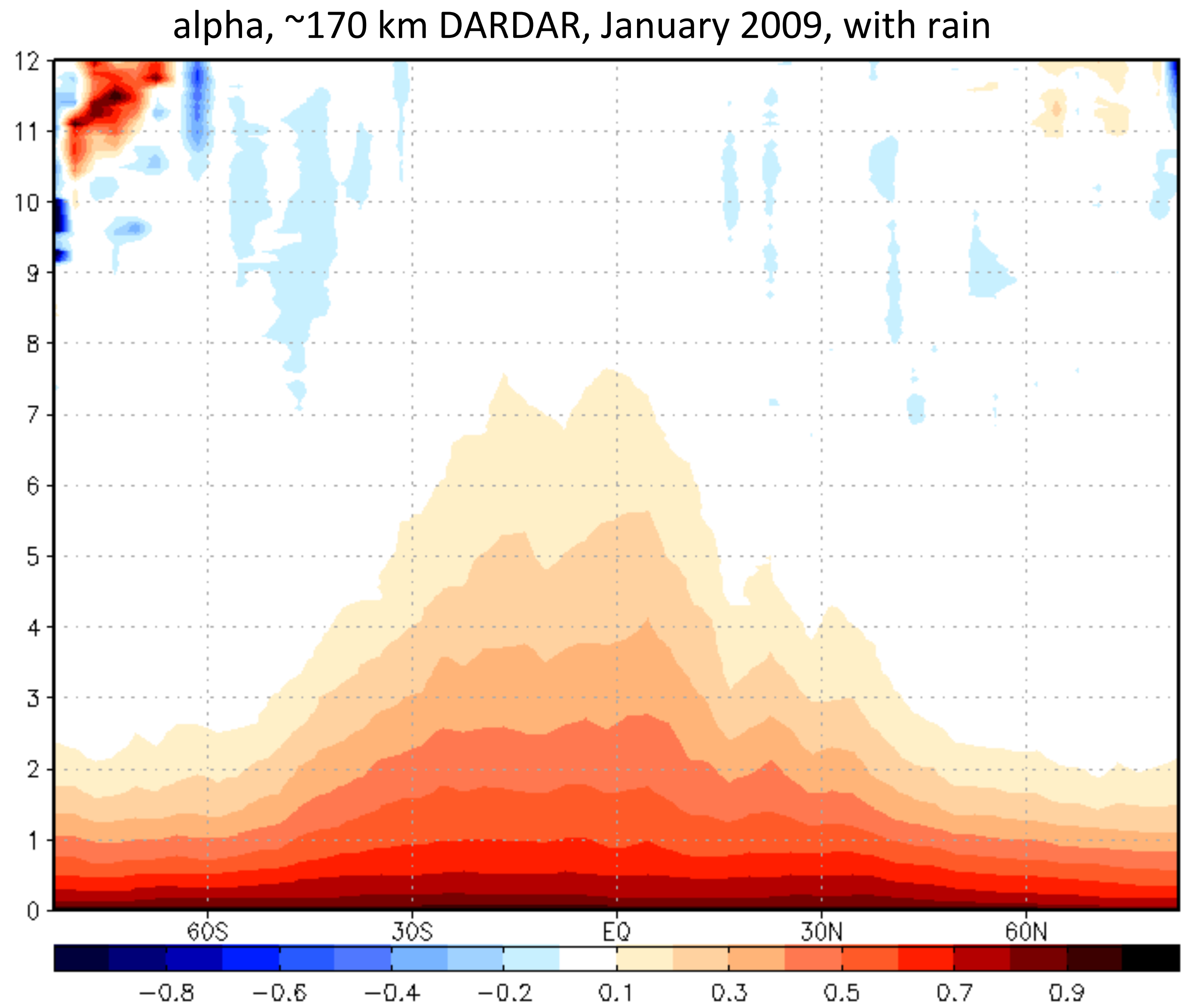
Zonal alpha from CloudSat/CALIPSO



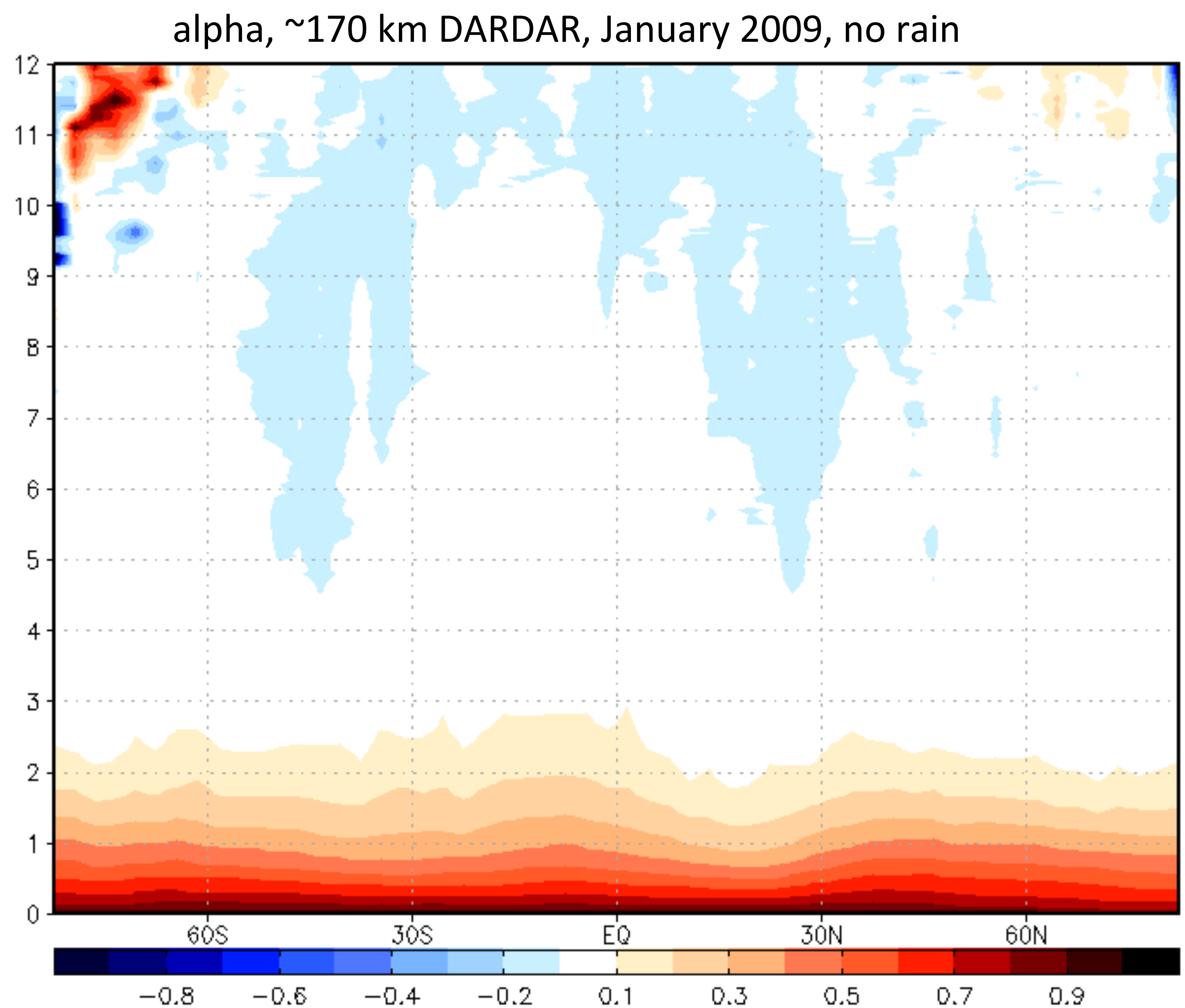
Zonal alpha from CloudSat/CALIPSO



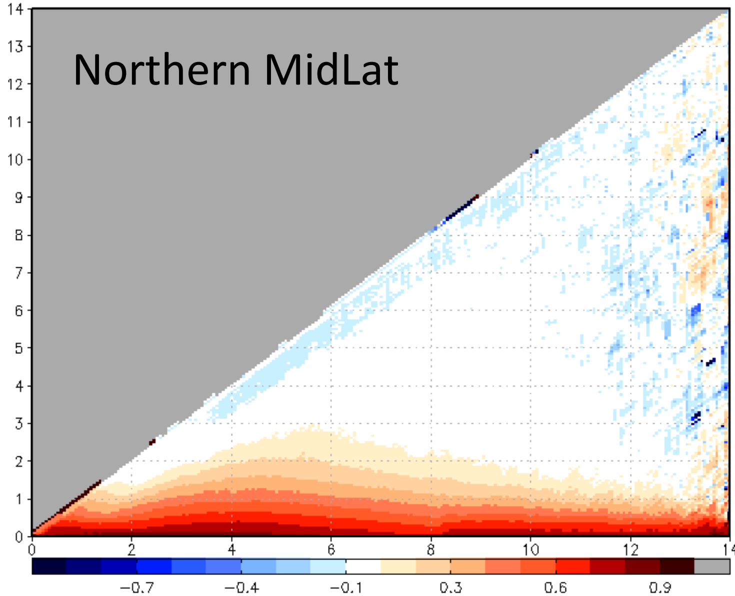
Zonal alpha from CloudSat/CALIPSO

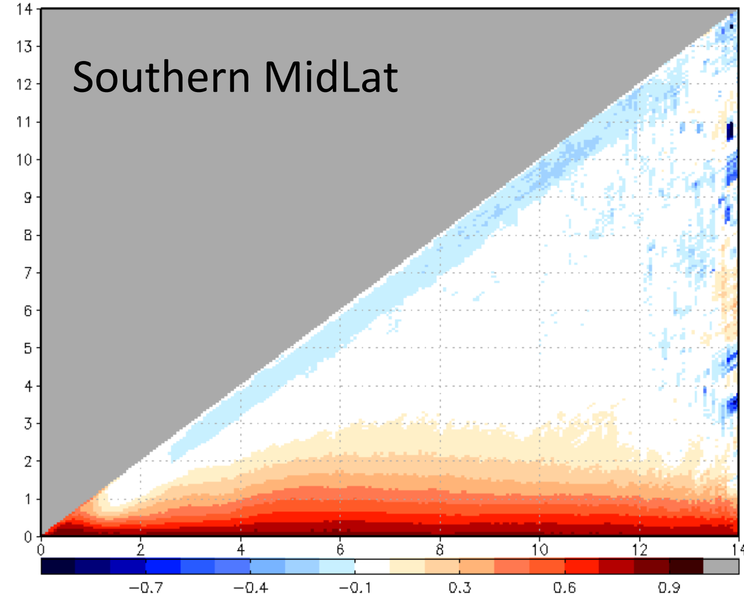


Zonal alpha from CloudSat/CALIPSO



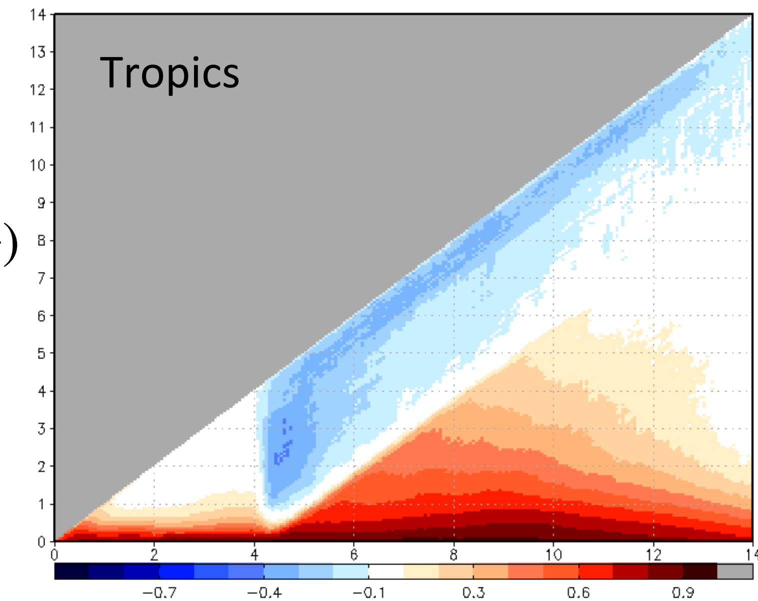
Height-dependent alpha from CloudSat/CALIPSO





$$a(\Delta z, \bar{x}, \bar{y}, z, t) = \exp\left(-\int_{\Delta z} \frac{dz}{L_c}\right)$$

$$L_c = L_c(\bar{x}, \bar{y}, z, t)$$

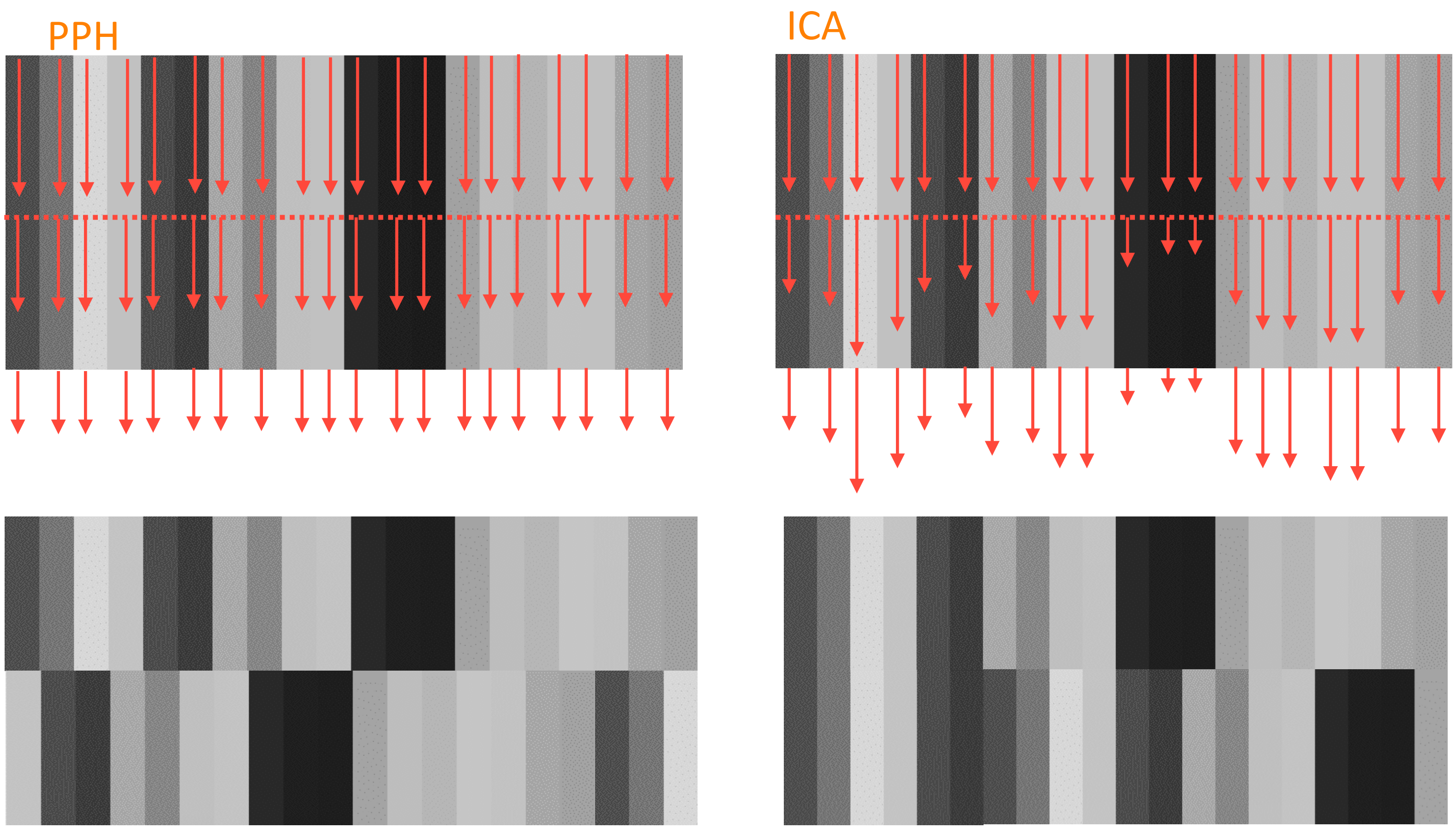


From DARDAR, no rain, January 2009

Cloud condensate overlap

Vertical overlap/correlations of condensate PDFs

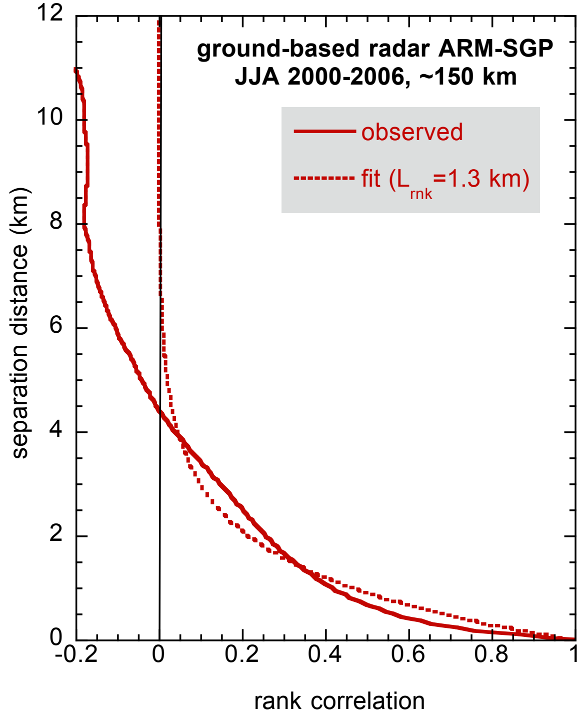
- Less studied
- Also affects radiative transfer
- Can be expressed as linear correlations of condensate amount or rank correlations

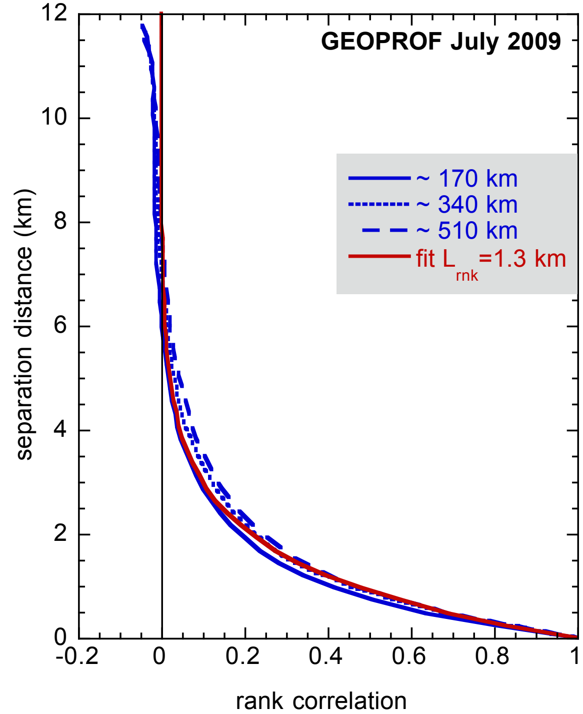


random correlation

more than random correlation

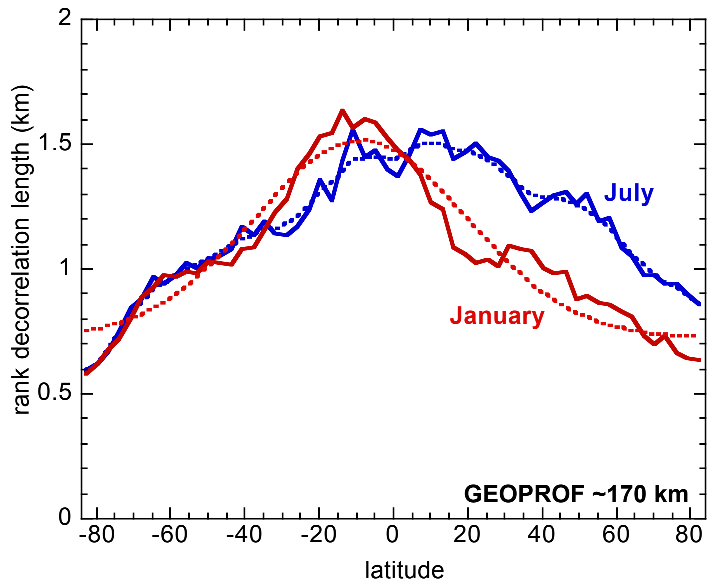
Observed condensate overlap from cloud radar





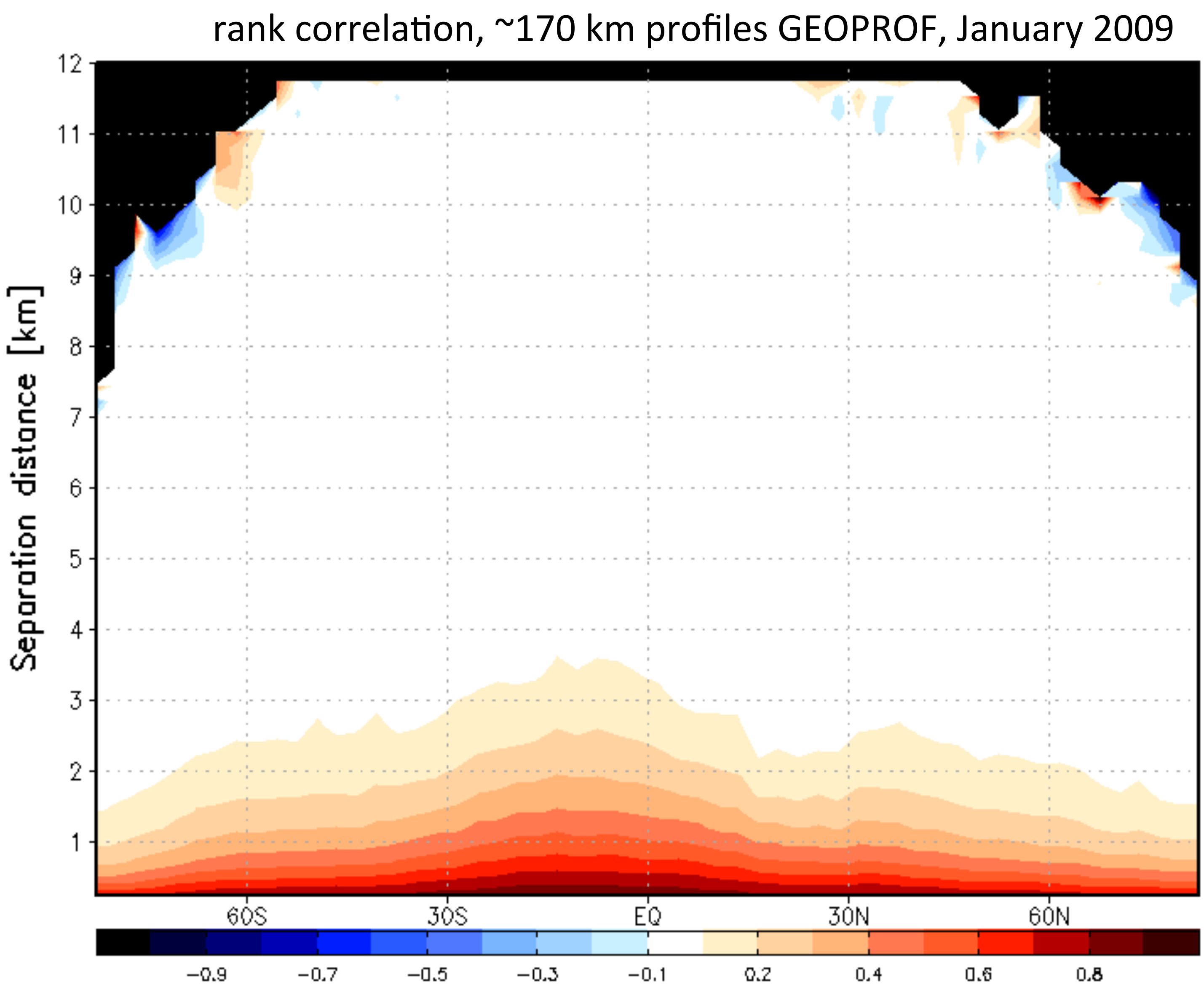
$$r(\Delta z, \bar{x}, \bar{y}, \bar{z}, t) = \exp(-\frac{\Delta z}{L_r})$$

$$L_r = L_r(\bar{x}, \bar{y}, \bar{z}, t)$$



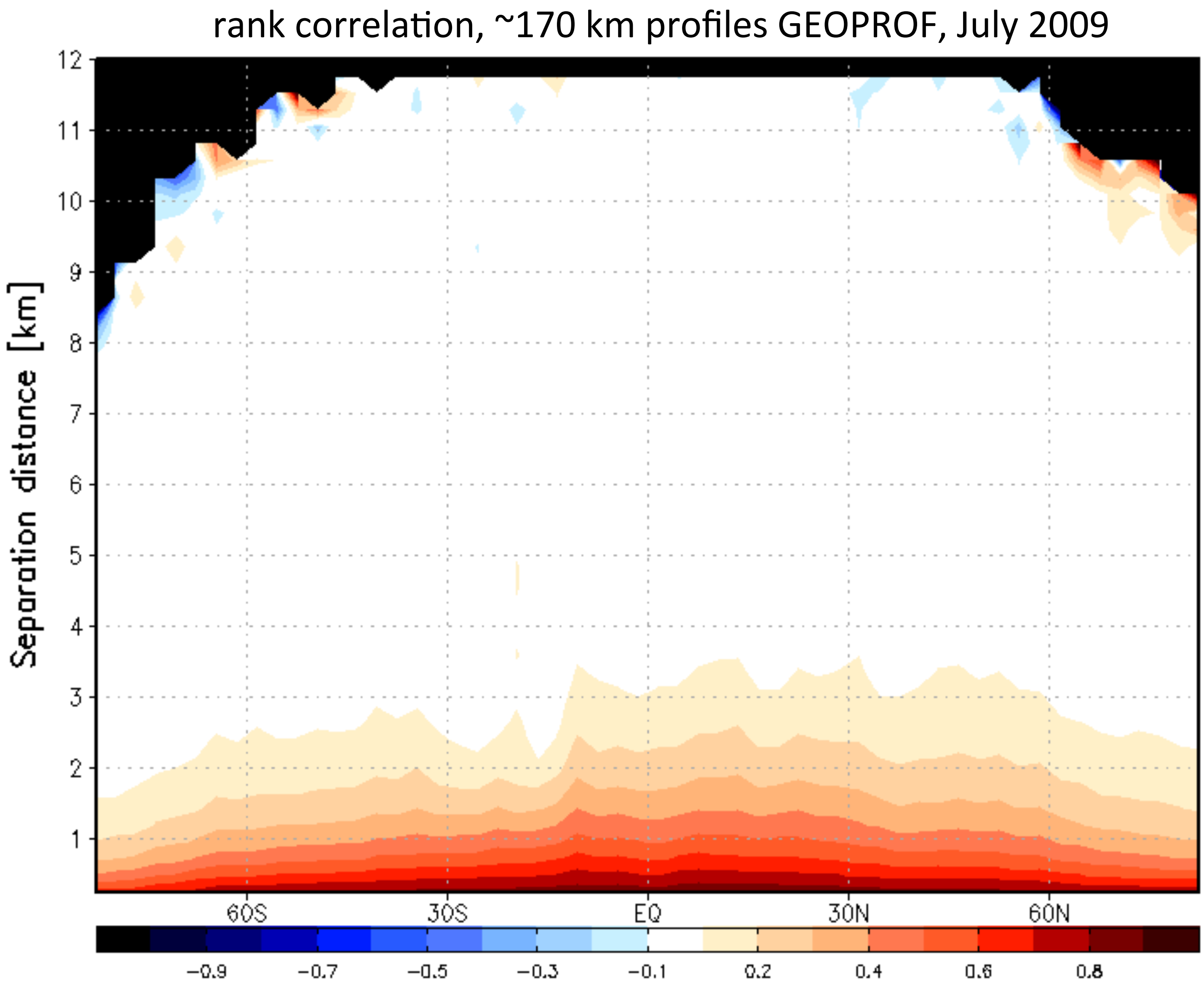
$$L_r = L_r(\bar{x}, y, \bar{z}, t)$$

Zonal rank correlation from CloudSat



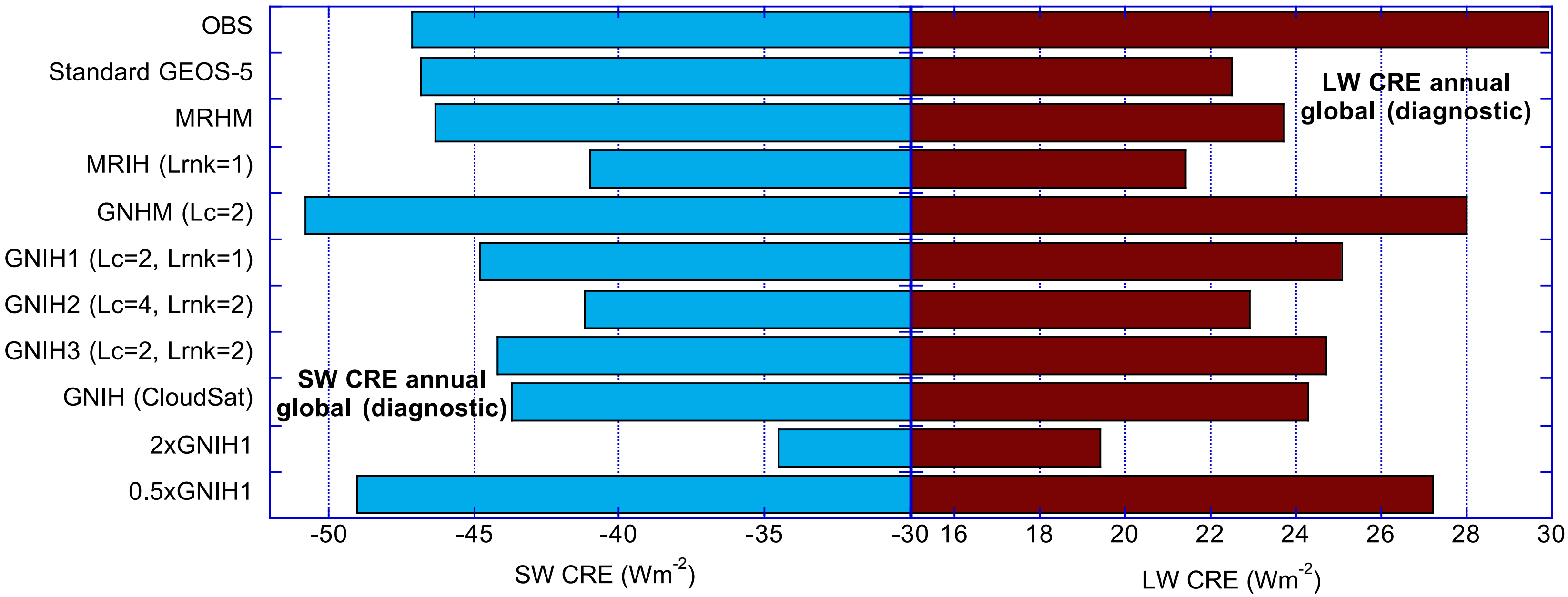
$$r(\Delta z, \bar{x}, y, \bar{z}, t)$$

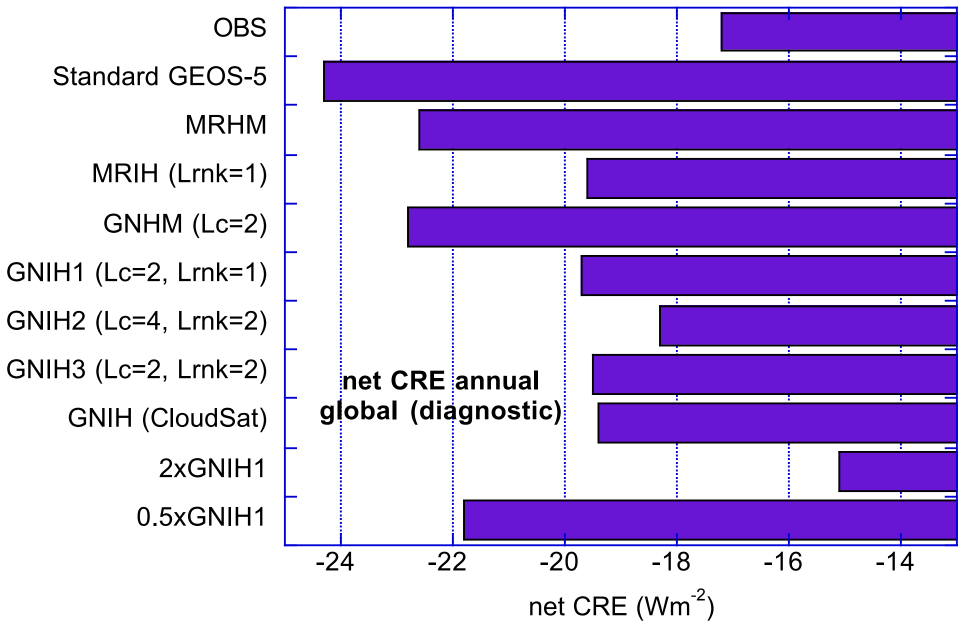
Zonal rank correlation from CloudSat



Implementation in GEOS-5 GCM

GEOS-5 global CRE





MR→GN, C_{tot} ⬆, CREs ⬆

HM→IH, CREs ⬇

L_c ⬆, C_{tot} ⬇, CREs ⬇

$L_r \equiv L_{rnk}$ ⬇, WP homogeneizes, CREs ⬆

Profile of cloud fraction and mean condensate is the same in all simulations!

Concluding thoughts

•Ultimate goal is for GCMs to produce observed features of CRE, including spatio-temporal variability and breakdown by cloud regime

•Cloudy RT in GCMs can be greatly simplified using cloud generators

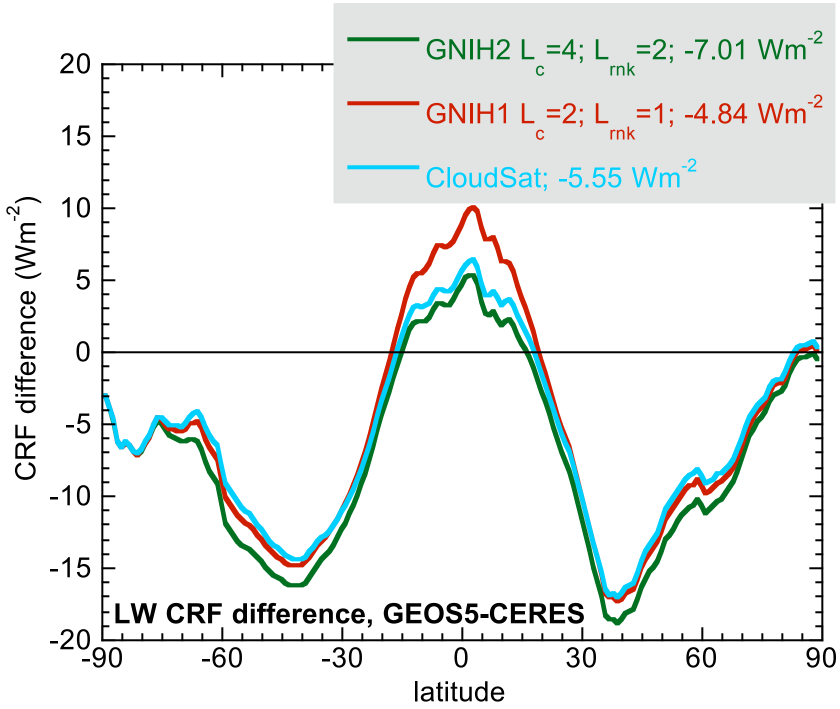
• Specification of cloud fields by generators requires vertical profiles of cloud fraction, cloud condensate, variability of cloud condensate, overlap of cloud fraction, and overlap of condensate PDFs

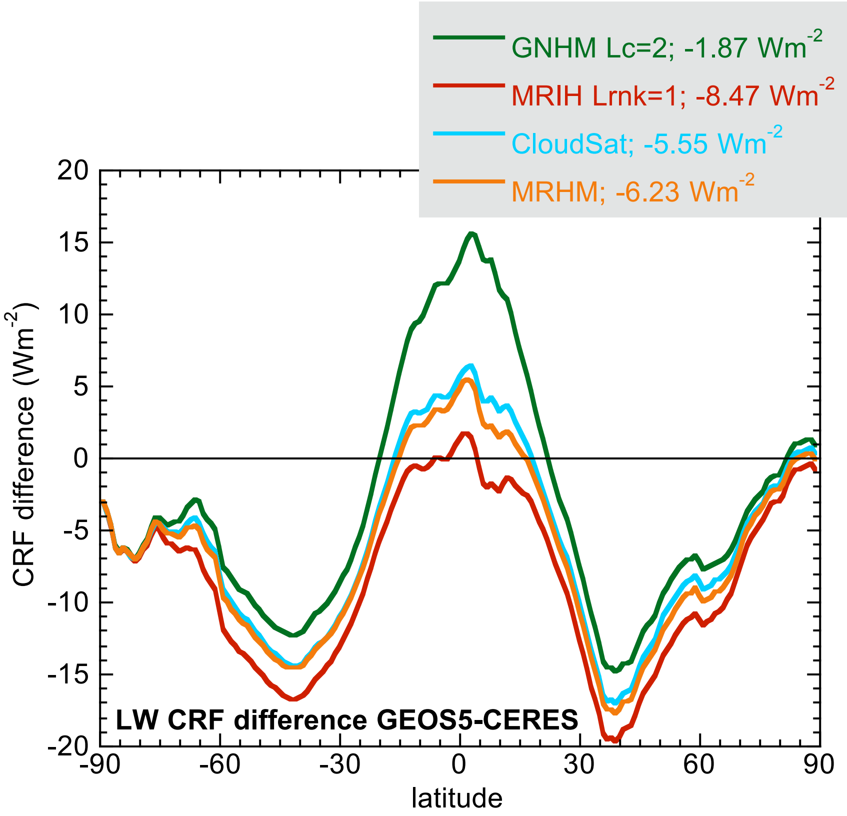
• Parameter specification and validation of cloud fields can now rely on observations, although there are still challenges

• We should continue to assess how much difference the detailed specification makes in the various GCMs with a wide range of sophistication in their cloud schemes

Additional Slides

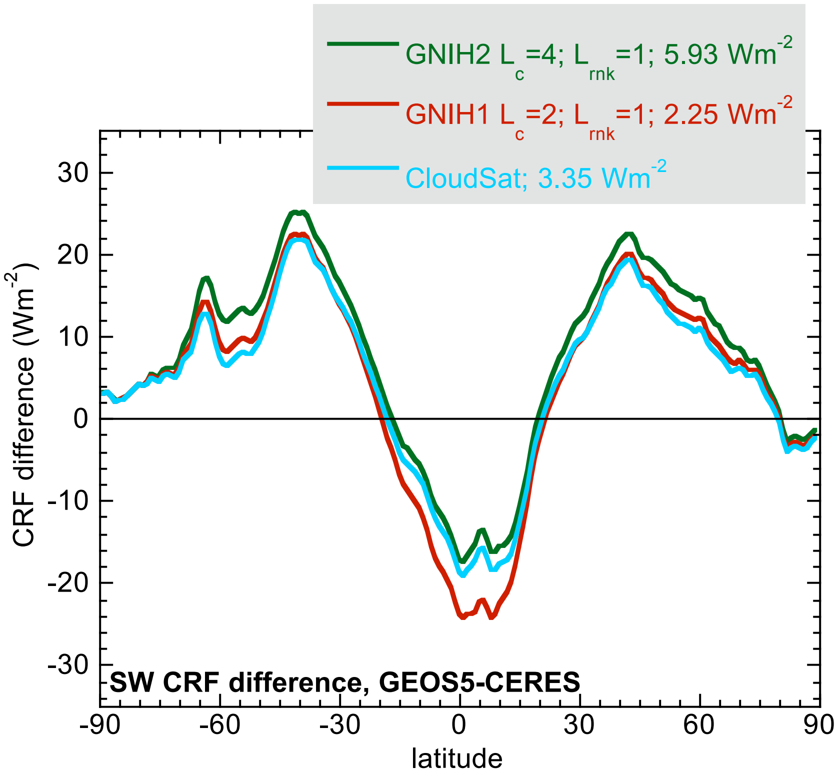
Zonal TOA LW CRF

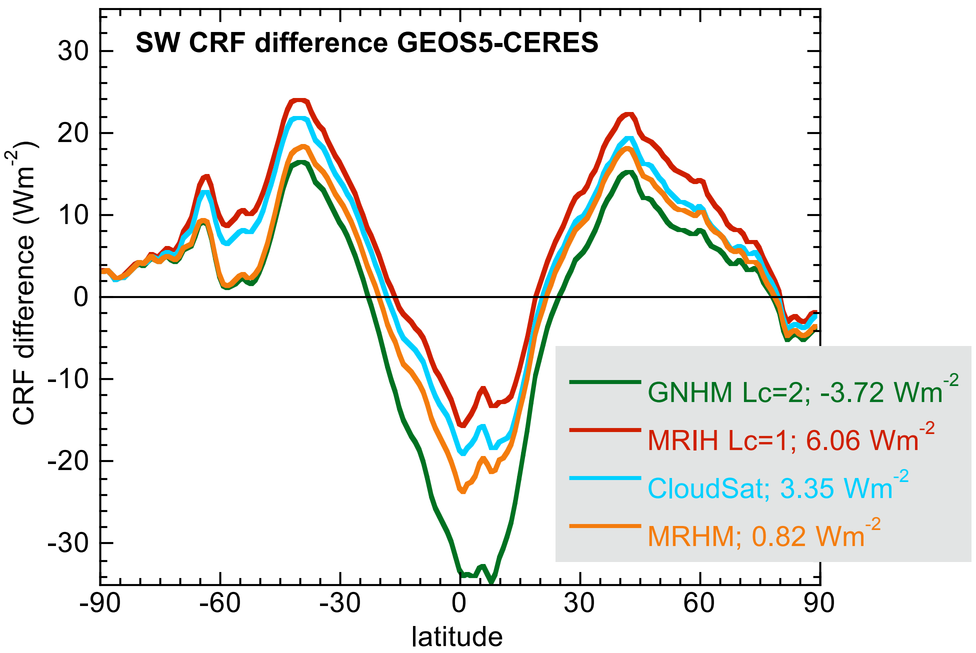




Positive means excessive LW TOA CRF

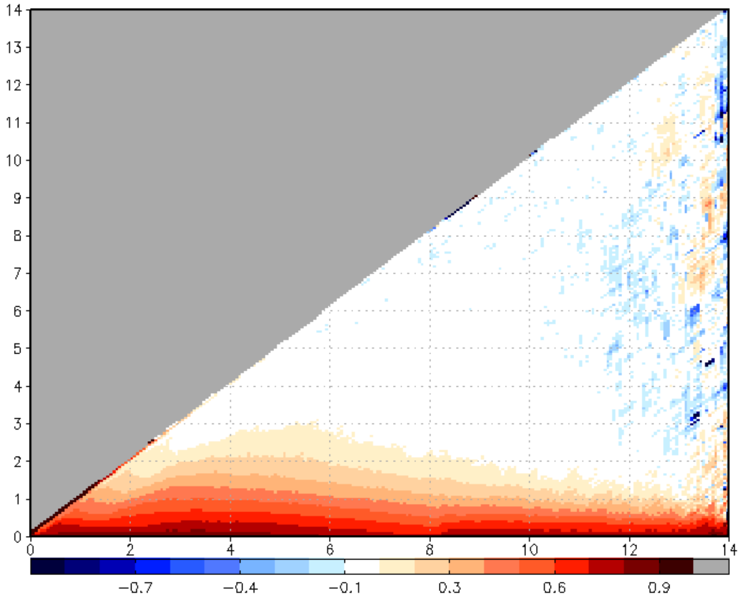
Zonal TOA SW CRF





Negative means excessive SW TOA CRF

With rain



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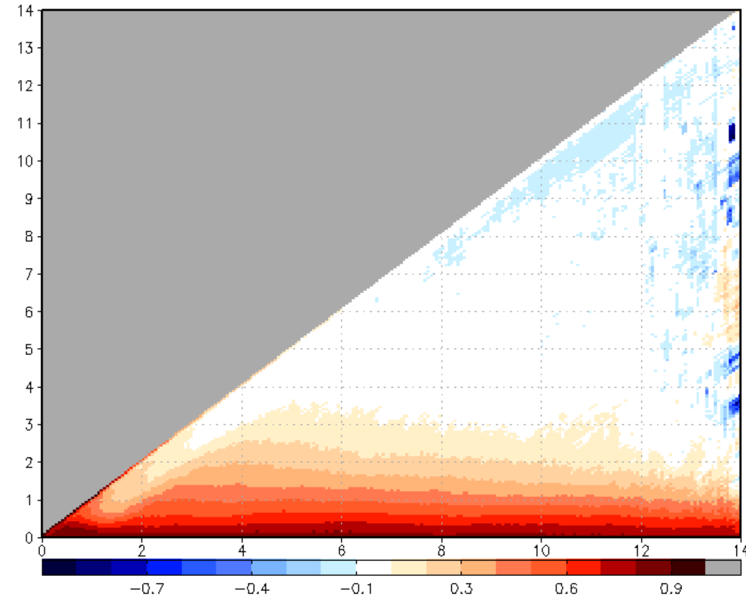

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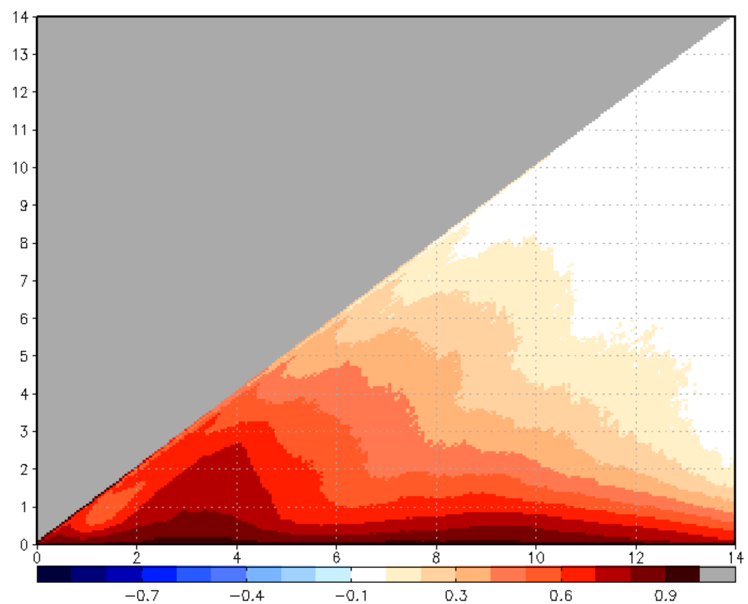

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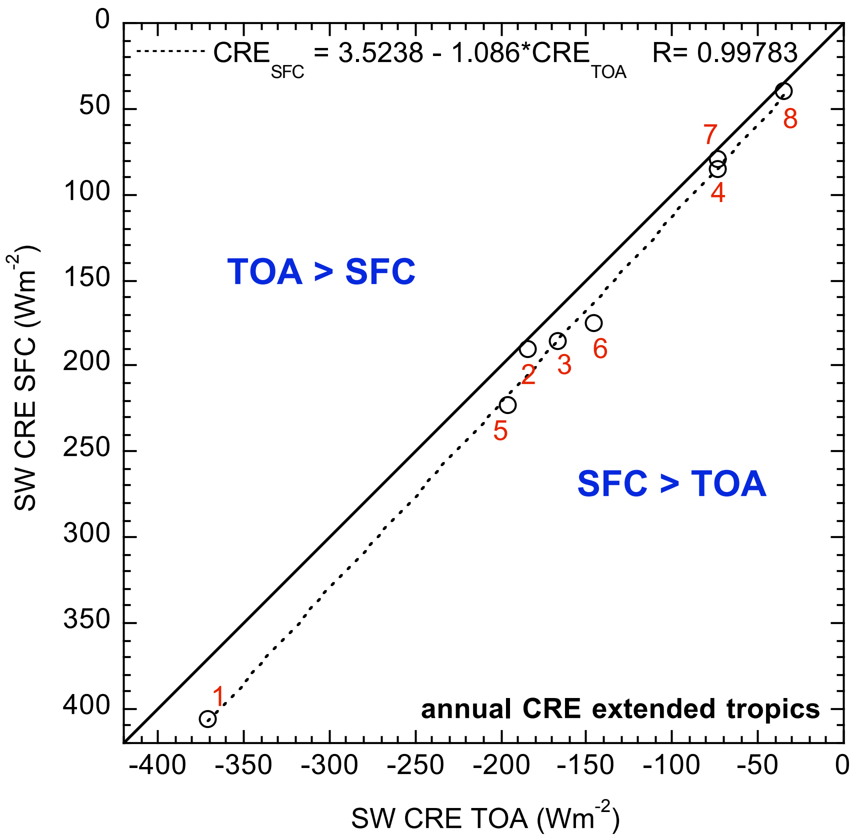
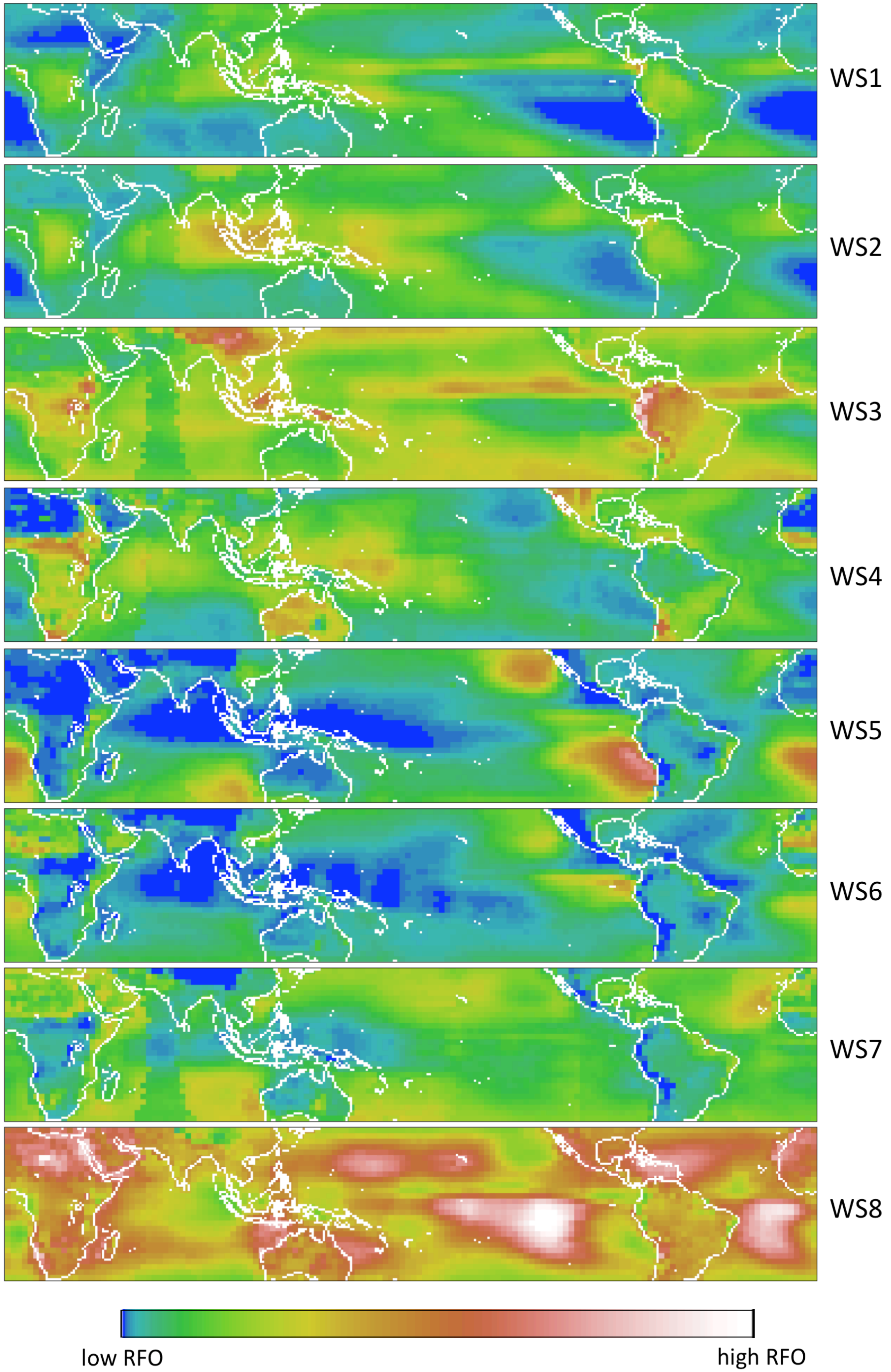
SFC vs TOA SW CRE, extended tropics



predictably linear and not very interesting!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low RFO
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